An introduction to the Australian and New Zealand flux tower network – OzFlux

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Abstract. OzFlux is the regional Australian and New Zealand flux tower network that aims to provide a continental-scale national research facility to monitor and assess trends, and improve predictions, of Australia's terrestrial biosphere and climate. This paper describes the evolution, design and current status of OzFlux as well as an overview of data processing. We analyse measurements from all sites within the Australian portion of the OzFlux network and two sites from New Zealand. The response of the Australian biomes to climate was largely consistent with global studies except that Australian systems had a lower ecosystem water-use efficiency. Australian semi-arid/arid ecosystems are important because of their huge extent (70%) and they have evolved with common moisture limitations. We also found that Australian ecosystems had similar radiation use efficiency per unit leaf area compared to global values that indicates a convergence toward a similar biochemical efficiency. The two New Zealand sites represented extremes in productivity for a moist temperate climate zone with the grazed dairy farm site having the highest GPP of any OzFlux site (2620 gC m^{-2} yr^{-1}) and the natural raised peat bog site had very low GPP (820 gC m^{-2} yr^{-1}). The paper discusses the utility of the flux data and the synergies between flux, remote sensing and modelling. Lastly, the paper looks ahead at the future direction of the network and concludes that there has been a substantial contribution by OzFlux and considerable opportunities remain to further advance our understanding of ecosystem response to disturbances including drought, fire, land use and land cover change, land management and climate change that are relevant both nationally and internationally. It is suggested that a synergistic approach is required to address all of the spatial, ecological, human and cultural challenges of managing the delicately balanced ecosystems in Australasia.

Keywords. Eddy covariance, flux tower networks, OzFlux, TERN, remote sensing, modelling, climate drivers, water use efficiency, carbon cycle.

1 Introduction

This paper is dedicated to the memory of our wonderful colleague and guiding light, Dr. Ray Leuning, who recently passed away.

1.1 The role of flux research in Australia

Global environmental change is one of the greatest challenges facing the planet (Steffen et al., 2011). To mitigate or adapt to global environmental change we must provide a scientific basis, underpinned by observation that is then scaled using models, for the development of national and global policies for improved land management (Vargas, 2002). Natural terrestrial ecosystems provide a range of services such as carbon sequestration and climate regulation, water balance, biodiversity, ecotourism, resources and food (Costanza et al., 1998; Eamus et al., 2005), yet they are at risk from climate change and variability, land use change and disturbance (Schroter et al., 2005). Natural ecosystems are also important sinks and sources of greenhouse gases that are sensitive to climate variability and can feed back to global climate change (Luo, 2007). Finally, changes in physical land surface properties can occur through land use change, disturbance and biogeographical shifts in ecosystems (Burrows et al., 2014) that can, in turn, alter biophysical coupling and feedback to alter weather and climate patterns at multiple scales (Beringer et al., 2014; Bonan, 2008).

Future climate and land use change may push ecosystems towards tipping points (Laurance et al., 2011), with deleterious changes to vegetation structure, composition and function, thus compromising ecosystem health and viability (Hughes, 2010). Of particular concern are potential increases in the effects of climate-induced physiological stress and interactions with other climate-mediated processes such as insect outbreaks and wildfire (Allen et al., 2010; Evans et al., 2013). This has important effects on carbon sequestration and greenhouse gases emissions because carbon stored in woody vegetation is vulnerable to increased fire risk through burning under climate change (Bowman et al., 2013). Death of vegetation from drought stress (Mitchell et al., 2014), extreme disturbance events, disease and pests could also result in increased carbon release to the atmosphere and changes to CO_2 emissions from soils (Hutley and Beringer, 2011). It is imperative that we understand the value and dynamics of ecosystem structure and function to ensure that we can manage them successfully into the future under environmental change (fire, pests and invasive species, future land-use and climate change) (Beringer et al., 2014; Hutley and Beringer, 2011).

To address global concern over rising atmospheric CO_2 concentrations and global climate change, there has been a growing need for studies of terrestrial ecosystems (Peters and Loescher, 2014). Studies using the eddy covariance technique from micrometeorological flux towers (Baldocchi, 2003) can contribute significantly to our understanding of ecological, biogeochemical, and hydrological processes by, amongst others:

1) providing accurate, continuous half-hourly to annual estimates of sinks and sources of greenhouse gases and water from ecosystems for carbon accounting and water management that is particularly important in such an arid country as Australia (Hutley et al., 2005; Raupach et al., 2013);

2) evaluating the effects of disturbance, topography, biodiversity, stand age, insect/pathogen infestation and extreme weather on carbon and water fluxes particularly cyclone, fire and heat waves in the Australian environment (Beringer et al., 2014; Bowman et al., 2009; van Gorsel et al., 2016; Hutley et al., 2013);

3) examining the effects of land management practices, such as harvest, fertilisation, irrigation, tillage, thinning, cultivation and clearing, especially agriculture in the region (Bristow et al., 2016; Campbell et al., 2015; Rutledge et al., 2015); and

4) producing important ground-truth data for parameterising, validating, and improving satellite remote sensing and global inversion products (Anav et al., 2015; Moore et al., 2016; Running et al., 1999; Schimel et al., 2015), particularly phenology (Ma et al., 2013; Moore et al., 2016) and the water balance.

Direct measurements from diverse biomes are essential for developing bio-geochemical and ecological models that diagnose and forecast the state of the land’s carbon and water budgets (Baldocchi, 2014b; Haverd et al., 2013a), which ultimately allow us to better respond and adapt to environmental change (Steffen et al., 2011). Given the utility of eddy covariance studies and the demand for these types of data, global and regional networks have come together to maximise their scientific value. The international network FLUXNET is a "network of regional networks" that coordinates regional and global analysis of observations from micrometeorological flux tower sites (Baldocchi et al., 2001), where at present over 650 sites are operated on a long-term and continuous basis. Biomes in FLUXNET include temperate conifer and broadleaved (deciduous and evergreen) forests, tropical and boreal woodlands and forests, crops, grasslands, chaparral, arid woodlands and scrublands, wetlands and tundra. Within FLUXNET are a number of regional networks such as European flux network, AmeriFlux (USA), AsiaFlux (Asia), Fluxnet Canada and OzFlux (Australia and New Zealand).

Australian vegetation is quite dissimilar to the northern Hemisphere as a result of continental isolation, tectonic-geological history and climate that results in the dominance of sclerophyllous, evergreen, woody species that do not fit into global plant functional types as discussed in Peel et al. (2005). Australian nutrient poor soils drive woody and sclerophyllous vegetation that are characterized by the presence of small, rigid, long-lived leaves (Peel et al., 2005). Importantly the OzFlux regional network is the only source of flux information for eucalypts and acacias that dominate the continent and are not significantly represented outside Australia. These vegetation groups occur primarily in arid and semiarid climates that dominate the landscape (this paper) and provide a crucial source of information in understanding the role of Australian semiarid vegetation in the global carbon cycle (Ahlström et al., 2015; Poulter et al., 2014). The eucalypts and acacias are predominately evergreen broadleaf plant functional types and represent a large fraction of this type globally that is represented in global climate models and information from this regional network would enable explicit ecological and physiological characteristics as well as the behaviour of Eucalyptus for future climate modelling.

The aim of this paper is to describe the evolution, design and current status of the Australian network of eddy covariance flux towers (OzFlux). Although New Zealand (NZ) flux sites have been an integral part of OzFlux from the outset and have made many important contributions (Campbell et al., 2014, 2015; Hunt et al., 2002, 2016; Rutledge et al., 2010, 2015) these sites have had a different history with typically shorter site records from primarily managed systems. Thus this paper will largely focus on Australian sites, with the addition of two of the NZ sites with longer multi-year records. An overview of data processing will be given first, followed by a summary and analysis of measurements from the OzFlux network. This is followed by an examination of synergies between flux measurements, remote sensing and modelling. The Australasian region comprises a wide range of ecosystems across a vast area where up-scaling using validated terrestrial biosphere modelling and remote sensing products is essential for complementing limited ground based biophysical observations. We will conclude by looking ahead at the future direction of the network.

1.2 Evolution of OzFlux in Australia

Australia and New Zealand have a long and rich history of significant contributions to the field of micrometeorology, including the development of theory around turbulence in and above plant canopies (Deacon, 1959; Priestley, 1967; Raupach and Thom, 1981; Webb et al., 1980) and instrumentation (Black and McNaughton, 1971; Deacon and Samuel, 1957; Leuning and Judd, 1996; Raupach, 1978; Taylor and Dyer, 1958), early efforts in scaling from leaf to canopy (Jarvis and McNaughton, 1986), along with some of the first field measurements (Denmead and McIlroy, 1970; Hicks and Martin, 1972). Initial micrometeorological field measurements were designed to validate the methodology and were often conducted in short campaigns over agricultural landscapes (Leuning et al., 2004). Micrometeorological measurements for research purposes accelerated in the 1990s with studies such as the Maritime Continent Thunderstorm Experiment (MCTEX) (Beringer and Tapper, 2002) and OASIS (Isaac et al., 2004). Long-term eddy covariance flux measurements in Australia were initiated at Howard Springs by Eamus et al. (2001) in 1997. In 2000 the wet temperate eucalypt forest site at Tumbarumba (Leuning et al., 2005) was established, followed by the tropical rainforest site at Cape Tribulation in 2001 (Liddell et al., 2016) (Fig. 1). Almost all of the sites in the OzFlux network have been initially established under short term research grants for specific purposes. However, due to the vision of the investigators who recognised the importance of long-term measurements, many of these sites were kept operational on minimal budgets, which has provided a legacy of important flux and ancillary data. At about this time the ‘OzFlux’ network was founded by Ray Leuning and colleagues at an inaugural meeting at Monash University in 2001 (Leuning et al., 2001). Leuning was the pioneer and leader of the network for many years and a mentor of many Australian and internationally based micrometeorologists and ecophysiologists (Cleugh, 2013). We dedicate this paper to him.

After the establishment of OzFlux, the community lobbied the Australian Federal Government to allocate financial resources for an ecological observational network. Over the next decade, the national collaborative research infrastructure strategy (NCRIS) established the terrestrial ecosystem research network (TERN, 2016) as a crucial platform to integrate datasets collected by different state agencies, CSIRO (Commonwealth Scientific and Industrial Research Organisation) and Universities for supporting decision-making to overcome Australia’s developing environmental problems (State of the Environment 2011 Committee, 2011). In 2009 initial funding was provided to TERN, which provided nominal support for many OzFlux sites along with other capabilities such as intensive ecosystem monitoring (SuperSites), remote sensing (AusCover), modelling (eMAST), TERN synthesis (ACEAS), coastal, soils and plot based networks (AusPlots), long term ecological research network facilities (LTERN) and transects (Australian Transect Network). OzFlux has had a central network capacity and from the outset this has been hosted by the CSIRO with data services provided at present through the NCI (Australia's National Computational Infrastructure). Despite the critical information provided by TERN and OzFlux Networks, recent funding and programmatic cuts may compromise sustained environmental research in Australia. New Zealand has a different history of flux sites, with long-term sites being slower to become established because of the shorter-term nature of the funding system. With much of the New Zealand economy centred on the agricultural sector, and efforts to ensure their sustainability and reduced greenhouse gas emissions, there has been a recent strong research focus on mitigation of soil carbon losses, including the use of EC techniques. Having experienced a large rate of native biodiversity loss, there have also been EC studies carried out in indigenous ecosystems, including tussock grasslands, forests, and wetlands.

2 OzFlux network architecture

2.1 Network overview

OzFlux aims to provide a regional national research facility for monitoring and assessing trends, and to improve predictions of Australasia's terrestrial biosphere and climate. It underpins the data collection and process understanding needed to: 1) support sound management of natural resources including water, carbon and nutrient resources for environmental and production benefits; 2) monitor, assess, predict and respond to climate change and variability; 3) improve weather and environmental information and prediction; 4) support disaster management and early warning systems needed to meet priorities in national security; and 5) ensure that Earth system models used to underpin policies and commitments to international treaties adequately represent Australasian terrestrial ecosystem processes.

OzFlux is focused on improving our understanding of the responses of carbon and water cycles of Australasian ecosystems to current climate and future changes in precipitation, temperature and CO_2 levels, as follows; 1) determine the key drivers of ecosystem productivity (carbon sinks) and greenhouse gas emissions; 2) assess how resilient ecosystem productivity is to a variable and changing climate and 3) quantifying the current water budget of the dominant Australasia ecosystems and how it will change in the future.

2.2 Network design

OzFlux in Australia has established an agreed set of core measurements and common protocols for measurements of carbon, water and energy fluxes across the national network (see section 3) to provide consistent observations to serve the land surface and ecosystem modelling communities. In addition to long-term fluxes of carbon, water and energy, ecosystem structural and functional properties are being measured, along with biodiversity and soil characteristics in collaboration with the TERN SuperSite Network (Australian SuperSite Network, 2015). The OzFlux network design is based on a hub and spoke model, wherein a critical element is the central node that coordinates the network¸ proposes protocols for measurements, has oversight of data processing and quality control, maintains a database to archive data from each site, data licencing and access via an online portal and provides scientific and technical training to flux station operators (Isaac et al., 2016). The central node implements a centralised database and provides feedback on live data feeds (equipment failure) and measurement quality to site operators. Individual site operators have responsibility for tower operation, data processing and quality control using OzFluxQC, gap filling, post-processing and are then required to deliver data streams to the central database. Through annual meetings, training workshops and technical support, OzFlux also provides a critical capacity-building opportunity to further build expertise, infrastructure, and data processing across the broader research community in ecosystem and climate sciences. Most NZ sites have developed separate data processing protocols and systems compared to the Australian part of OzFlux, with uptake of EddyPro post-processing becoming more standard in the last few years.

2.3 Network climate and biome space

The modified Köppen climate classification of Stern and Dahni (2013) shows that the greater part of the Australian continent is either desert climate (i.e. arid) (38% of land) or grassland climate (i.e. semi-arid) (36% of land). Only the south-east and south-west corners have a temperate climate (10%) and moderately fertile soil (McKenzie et al., 2004). The northern third of the continent is dominated by sub-tropical (7%), tropical (9%) and grassland (36%) climates, with tropical rainforests, tropical savanna, grasslands and deserts the dominant ecosystems. Mean annual precipitation (MAP) across the continent varies from 134 to 2804 mm, and mean annual temperature (MAT) varies from 3.8 to 29.0 ºC (from 1961-1990 MAP and MAT gridded data at 0.1 degree resolution (Bureau-of-Meteorology, 2013)). Many individual stations exceed the spatially gridded data due to topographical/spatial issues such as Mount Bellenden Ker that has the highest mean annual rainfall of any Bureau of Meteorology station at 8173 mm (station ID 031141 for period 1973 to 2015). The Australian OzFlux sites are relatively uniformly distributed over this climate space (Fig. 2). NZ's climate is more temperate maritime with a wide latitudinal range, but generally younger landscapes and precipitation is generally evenly distributed except for strong precipitation gradients associated with mountain chains in both main islands.

Using the modified Köppen scheme, Stern and Dahni (2013) showed that the major Australian climate zones were (from largest to smallest by area) desert, grassland, temperate, tropical, sub-tropical, equatorial and polar. Stern and Dahni (2013) also reported changes in the distribution of Australian climate zones due to climate change during the past century, the most notable one being the contraction of the area covered by ‘desert' climates (from 51.1% to 37.9%) and the corresponding increase in the area covered by 'grassland' (from 26.3% to 36.1%) and 'tropical' (from 5.5% to 9.0%) climates. Therefore, a large portion of the continent is arid or semi-arid (74%) and ecosystems in the semi-arid climate zone have been recognized recently as of critical important in driving inter-annual variability in the global CO_2 growth rate cycle (Bastos et al., 2013; Poulter et al., 2014). Poulter et al. (2014), Haverd et al. (2015) and Cleverly et al. (2016a) found that a large sink anomaly in 2011 was mainly attributed to increases in net primary productivity (NPP) across the semi-arid regions of the southern hemisphere (30-60% from Australian semi-arid ecosystems), during a large La Niña event where Australian MAP exceeded the long-term by 55% (Boening et al., 2012). As a consequence the water-limited ecosystems responded by rapid growth and productivity. Ahlström et al. (2015) subsequently demonstrated that both the inter-annual variability and trend of the global sink were dominated by semi-arid ecosystems whose carbon balance is strongly associated with circulation-driven variations in both precipitation and temperature. This and similar dynamics have been captured at the semi-arid sites in OzFlux as discussed in Eamus and Cleverly (2015) and Cleverly et al. (2016a).

In terms of vegetation classification, we have used the Interim Biogeographic Regionalisation for Australia v. 7 (IBRA) (Environment, 2012) throughout (Table 1, Fig. 1) to describe the Australian vegetation types (bioregions) and ecoregions (global classification). Flux sites located in natural vegetation (n=27) (Table 1) cover a wide geographical and biome space, although each ecoregion is not equally represented (Table 2, Fig. 1). Despite the dominance of deserts and xeric shrublands (49%) and the areal importance of arid/semi-arid climate (74%), only a small fraction of the OzFlux sites (two towers, 8% of the network) are located in this region. There is a strong representation of flux towers in the tropical and sub-tropical moist broadleaf forests. In addition, of the 34 flux tower sites in Table 1, only six (16%) are located in predominantly agricultural/managed/modified landscapes. Bristow et al. (2016) provide a specific case study of land use transitions in tropical savannas.

Of the 11 currently TERN funded OzFlux sites 10 are also TERN SuperSites that carry out a standard set of measurements using agreed protocols that provide a considerable set of ancillary measurements available at each OzFlux site (http://www.supersites.net.au). Included in this suite of data are soil characterisation, plant biodiversity, leaf area index (LAI), vegetation structure, groundwater data, stream chemistry and faunal biodiversity (Karan et al., 2016). In addition, each SuperSite has been supported by the TERN Auscover remote sensing facility with ground based (terrestrial laser scanner) and air-borne (lidar, hyperspectral) remote sensing data collected in a 5 km x 5 km pixel centered at each tower. Like all TERN data these data sets are publically available from the TERN data portals with metadata made available across the portals at TERN (http://portal.tern.org.au).

3 Eddy covariance data

3.1 Instrumentation and data collection

In 2016 the OzFlux network comprised 23 active flux towers across Australia and there were 12 active flux tower sites in New Zealand. (Fig. 2, Table 1). There is a high degree of consistency in instrumentation across the OzFlux network. The general tower configuration in Australia consists of a CSAT3 sonic anemometer (Campbell Scientific, Logan, Utah, USA) and a Li-7500[A] (LI-COR, Lincoln, Nebraska, USA) or EC-150/155 (Campbell Scientific, Logan, Utah, USA) infra-red gas analyser mounted at the top of the tower. All sites record three components of the wind field, air temperature and the H_2O and CO_2 concentrations at 10 or 20 Hz. Complementary measurements of slow response wind speed (Gill Instruments Ltd, Lymington, Hampshire, UK; R.M. Young, Traverse City, Michigan, USA), air temperature and humidity (various, Vaisala, Helsinki, Finland) are also made at at least one height. Soil water content (various, Campbell Scientific, Logan, Utah, USA), soil temperature (TCAV, Campbell Scientific, Logan, Utah, USA) and ground heat flux (CN3, Middleton, Newtown, VIC, Australia; HFT3, Campbell Scientific, Logan, Utah, USA; HFP01, Hukseflux, Delft, The Netherlands) are measured in soil pits adjacent to the towers and often replicated in space and depth. Radiation (4-component) is measured at the tower top (CNR1, CNR4 Kipp & Zonen; NR01 Hukseflux; Delft, Netherlands). Precipitation (CS702, Campbell Scientific, Logan Utah, USA; CS7000, Hydrological Services, Warwick Farm, NSW, Australia) is measured at ground level at most sites. Systems measuring the profiles of H_2O and CO_2 concentration in the canopy are installed at Tumbarumba, Wombat Forest, Cumberland Plains, Whroo and Robson Creek. Details of the instrumentation at each site are available from the OzFlux web site (http://www.ozflux.org.au/monitoringsites/index.html). New Zealand sites have more variable instrument systems, with earlier measurements made using closed path gas analysers (LI-6262, LI-7000 LI-COR, Lincoln, Nebraska, USA), but now with open path and "enclosed" path sensors used (LI-7500, LI-7200, LI-COR, Lincoln, Nebraska, USA).

Data are recorded at most sites by Campbell data loggers (various, Campbell Scientific, Logan, Utah, USA). Tumbarumba, Otway and Virginia Park use purpose-built micro-computers. At all sites using Campbell data loggers, the averaged and high frequency data are retrieved via modem or recorded on compact flash (CF) cards, which are retrieved periodically, read and archived at the site PI’s institute.

3.2 Data quality control and post-processing

Most Australian sites with Campbell data loggers begin with the average (over 30 minutes) covariances recorded by the logger and processed through six levels using the OzFluxQC standard software processing scripts. NZ sites typically calculate fluxes on-board the datalogger, but sites reprocess raw high frequency data (e.g. using EddyPro). For details of the Australian processing see Isaac et al. (2016) but in brief, levels 1, 2 and 3 represent the raw data as received from the flux tower (L1), quality-controlled data (L2) and post-processed, corrected but not gap-filled data (L3). Sites submit their data to

FLUXNET at L3. Levels 4, 5 and 6 represent data with gap-filled meteorology (L4), gap-filled fluxes (L5) and partitioned into gross primary production (GPP) and ecosystem respiration (ER) (L6). The L1 to L3 data used in this paper have been produced using OzFluxQC (Isaac et al., 2016) and Level 3 are then gap filled and partitioned using the Dynamic INtegrated Gap filling and partitioning for Ozflux (DINGO) system developed by Beringer as described in Donohue et al. (2014). Data from NZ sites were gap-filled and partitioned using advanced neural networks (following Papale and Valentini (2003) as implemented in Matlab (The Mathworks, Natick, Massachusetts, USA).

OzFluxQC quality control measures are applied at L2 and include checks for plausible value ranges, spike detection and removal, manual exclusion of date and time ranges and diagnostic checks for all quantities involved in the calculations to correct the fluxes. The quality checks make use of the diagnostic information provided by the sonic anemometer and the infra-red gas analyser. For sites calculating fluxes from the averaged covariances, post-processing includes 2-dimensional coordinate rotation, low- and high-pass frequency correction, conversion of virtual heat flux to sensible heat flux and application of the WPL correction to the latent heat and CO_2 fluxes (see Burba (2013) for general description of the data processing pathways). Steps performed at L3 include the correction of the ground heat flux for storage in the layer above the heat flux plates (Mayocchi and Bristow, 1995) and correction of the CO_2 flux data for storage in the canopy (where available). OzFlux data are available at http://data.ozflux.org.au/.

4 Results - Biotic and abiotic controls on land-surface exchanges

We used the conceptual framework for carbon balance terms following Chapin et al. (2006), including their sign convention where net and gross carbon uptake (net ecosystem production (NEP) and gross primary production (GPP)) are positive directed toward the surface and ecosystem respiration (ER) is positive directed away from the surface. For ease, the following analysis has been aggregated by ecoregion (Table 2) from the individual site data that are detailed in Table 3. Note that the number of years representing each site is different. Net ecosystem production (NEP) across the ecoregions varied with forests generally the strongest sink (followed by grasslands, savannas and shrublands). The Mediterranean ecosystems were close to carbon neutral and deserts and xeric shrublands were a carbon source overall (Table 3). This can be compared to AsiaFlux, where NEP varied across the network between -2 and 8 tC ha^{-1} yr^{-1} with the differences due mainly to tree species and mean annual temperature (MAT) (Yamamoto et al., 2005). Across all of the OzFlux sites the average NEP was 1.8 tC ha^{-1} yr^{-1} which is comparable to the global average of 1.6 tC ha^{-1} yr^{-1} (Baldocchi, 2008).

There was also a large variation in the seasonality of carbon fluxes (Fig. 3) between the ecoregions, which followed patterns in temperature and/or rainfall and moisture availability across Australasia. Tropical moist broadleaf forests had the smallest seasonality followed by savannas, which are seasonally water limited with seasonal variation driven by large dry season decline in fluxes from the C_4 grass-dominated (Whitley et al., 2011). Tropical grasslands showed the largest seasonality and notably had the largest peak mean monthly NEP of 4.5 gC m^{-2} d^{-1} which occurs after re-sprouting and green-up during rapid growth when soil respiration remains low (Fig. 3a). Only later during the season, when the grasses senesce is carbon returned to the atmosphere via fire and respiration and to the soil through litter and root carbon. Across the ecoregions, GPP generally scaled with leaf area index (LAI) and water availability (precipitation) (Fig. 5), with desert shrublands having the lowest GPP and tropical moist broadleaf forests having the highest (Table 2) (Fig. 3b). Tropical grassland GPP was similar to that of forests during the monsoonal summer wet season; however, GPP in the grassland collapsed to near zero during the dry season (Fig. 3b). In general, the magnitude of ecosystem repiration (ER) was near a constant fraction of GPP across the annual cycle for each ecoregion (Fig. 3c and Fig. 4).

Following on from the average fluxes (discussed above), there are periods when substantial inter-annual variability is superimposed on Australia’s mean climate (Cleverly et al., 2016b) and this variability has been captured by bush poet Dorothea Mackellar as the land of “droughts and flooding rains” (Mackellar, 2011). Australia's weather is primarily driven by three climate modes: El Niño-Southern Oscillation (ENSO), the Indian Ocean dipole (IOD) and the southern annular mode (SAM) and when these climate modes synchronise, fluctuations between drought and extreme precipitation can be extreme and rapid (Cleverly et al., 2016b). Extreme weather across Australia during the 21st century has been the result of synchronisation amongst these climate modes, such that wet conditions created by one climate mode were reinforced by similarly wet conditions in the other modes (Cleverly et al., 2016b). The El Niño phase brings warmer and drier than average conditions, whilst cooler and wetter conditions are characteristic of La Niña phase (Nicholls et al., 1991; Power et al., 1999) and together all three modes of variability influence patterns of vegetation fluxes (Cleverly et al., 2016b). In general, rainfall is limiting to productivity across much of Australia whereas temperature is not. Raupach et al. (2013), through a modelling study, showed that evapotranspiration (ET) from Australian ecosystems is expected to increase with increasing precipitation and temperature, but decrease with rising CO_2 through increased plant water-use-efficiency. They also showed that NEP is expected to increase with rising CO_2 concentration but this may be offset by reduced NEP in response to warming. Much of the network is, either directly or indirectly, contributing critical data to refine our understanding of the drivers of NEP and the role of precipitation events on carbon and water cycles (Chen et al., 2014; Eamus et al., 2013a; Kanniah et al., 2011; Ma et al., 2013). One of the major impacts on New Zealand ecosystem carbon and water exchanges occurs as a result of seasonal drought. For grazed pasture, Rutledge et al. (2015) and Mudge et al. (2011) showed that NEP of a dairy farm during a year with a severe drought largely recovered to pre-drought levels over the remainder of the year because of the year-round growing conditions. In a raised peat bog, Goodrich et al. (2015a) found that GPP was reduced under conditions of elevated VPD common during drought, and Goodrich et al. (2015b) described reductions in methane fluxes for up to six months after water tables recovered following drought.

Climate variability and land management also drives recurrent fire on the Australian landscape, with Australia being one of the most fire-prone continents on earth (Bradstock et al., 2012). Using AVHRR satellite data from 1997-2005, Russell-Smith et al. (2007) showed that the distribution of large fires varied with biophysical variables, and continental fire patterns varied substantially with rainfall seasonality. Their results highlight the importance of anthropogenic ignition sources, especially in the northern wet–dry tropics and demi-arid/arid Australia. These recent patterns differ greatly from assumed fire regimes under Indigenous occupancy, and the differences in fire regime can cause significant effects on biodiversity that are likely to increase in the future (Russell-Smith et al., 2007). Interestingly, a number of Australian flux sites have been influenced by wildfire including: 1) a catastrophic, stand replacing wildfire in the old growth Mountain ash forests (*Eucalyptus regnans,* Au-Wac) during February 2009; 2) a fire at Calperum (Au-Cpr) in January 2014 that burned spinifex (*Triodia* sp) ground cover and leaves and branches of eucalypt species; 3) frequent and relatively low intensity fires across all the savanna sites (Au-How, Au-Ade, Au-DaS, Au-Dry) and at a tropical grassland (Au-Stp). Many of the research questions, particularly in savannas, are focused on the influence of burning at scales from leaf to landscape (Beringer et al., 2003, 2007, 2014).

Annual NEP as measured by flux towers is the difference between GPP and ER (Chapin et al., 2006). On a site-by-site basis across the network, ER and GPP are strongly correlated (r^2=0.93) (Fig. 4) (Reichstein et al., 2005). The slope of the line is 0.76, which compares well with an international synthesis that found a slope of 0.77 (Baldocchi, 2008). The results from the international study are shown in the background of Fig. 4, where disturbed sites fall along a secondary line (carbon source). Interestingly, few Australian sites are close to this disturbed level, except for Au-RDF, which had undergone a transition from savanna to pasture, and Au-Wrr, which is a tall forest with potential advection issues such that the ratio of GPP to ER might be unreliable. Despite this, there are many flux towers in the network that have captured varying levels of disturbance including fire, insect attack (van Gorsel et al., 2013), logging , grazing, termite herbivory (Jamali et al., 2011) and tropical cyclones (Hutley et al., 2013). Curiously, as pointed out by Baldocchi (2008), Australian systems that are burnt frequently (i.e. savannas) do not fall in line with other types of disturbance (Fig. 4) because these low intensity fires form a type of rapid respiration that does not significantly alter carbon pools on annual timescales, either for vegetation (Beringer et al., 2003, 2007) or as soil carbon (Allen et al. 2014).

We used a simple heat map to identify correlations between fluxes, driving variables and functional attributes of Australian ecosystems (Fig. 5). We used the following ecosystem indices: radiation use efficiency (RUE) following Garbulsky et al. (2010); ecosystem water-use-efficiency (WUE* calculated as the ratio of GPP to AET, where * indicates ecosystem scale) and inherent ecosystem WUE* (IWUE* calculated as the ratio of GPP to AET x VPD) following Beer et al. (2009); Bowen ratio (BR) is defined as the ratio between sensible and latent heat fluxes (Bowen, 1926); leaf area index (LAI) obtained from the average of the MODIS MOD15 product for the site years available and has been de-spiked using the procedure described in Kanniah et al. (2009a); and rainfall use efficiency following Huxman et al. (2004) and defined as the ratio of GPP to precipitation. In determining RUE we calculate the absorbed PAR using the MODIS fraction of absorbed PAR product (MODIS MOD15 fPAR) and flux tower PAR data. Here we use MODIS LAI purely in a relative sense to assess differences in cover and how they may influence the observed fluxes. Many sites have no LAI measurements and some others have ad-hoc measurements over time. In addition, we know that the magnitude of LAI from the MODIS LAI product utilised in this paper varies from site based estimates but has been used for consistency.

In general, the major controls on site-averaged GPP and NEP were precipitation, vapour pressure deficit (VPD) and LAI (Fig. 5) as expected (Yi et al., 2010). Counterintuitively, incoming solar radiation (F_{sd}) was negatively correlated with GPP, suggesting that F_{sd} is not limiting; we speculate that the negative correlation is explained by an association between regions of high sunlight (F_{sd}) in arid-semi/arid climates that have vegetation that tends to have lower GPP due to water limitations. Given LAI is such an important driver (and LAI is strongly correlated with precipitation), we normalised the fluxes and indices by dividing them by LAI. Subsequently, these normalised ratios showed that after accounting for LAI, GPP was only weakly positively correlated ($r<0.3$) with temperature (T_a) and negatively correlated with precipitation (Fig. 5). We hypothesise that the negative correlation of GPP/LAI with rainfall is due to the lower radiation due to cloud associated with high rainfall.

We further explored the relationships of GPP *versus* mean annual temperature (MAT) and mean annual precipitation (MAP). We followed Garbulsky et al. (2010) to allow for a direct comparison with that global study where they used 35 eddy covariance (EC) flux sites (none from Australia) spanning between 100 and 2200 mm MAP and between -13 and 26°C MAT. The global relationships are shown in the background to aid comparison (Fig. 6). The range of GPP across the OzFlux sites was 32 to 2616 gC m^{-2} yr^{-1} which is consistent with the range of global values (50 to 3250 gC m^{-2} yr^{-1}) (Fig. 6). The relationship between GPP and MAP follows the global function (Fig. 6a) although the range of MAP across the Australian sites is larger than is observed from the global flux network due to the high MAP of the sites in the tropical rainforest region. In contrast to the global study, MAT had no significant relationship with GPP (Fig. 6b) in Australia. This is partly because there are no sites in Australia with MAT below zero and MAT is generally not limiting to GPP, however, high temperature can limit NEP in the desert ecoregion (Cleverly et al., 2013, 2016a). The most highly productive sites were obviously not moisture limited, including cool temperate forests (MAT < ~12ºC), hot wet tropical forests (MAT > ~25 ºC, MAP > 2000 mm) and grazed pasture (MAT ~14 ºC, MAP ~1200 mm) (Fig. 6a, b). The peak in GPP in Australian forests seen at MAT ~12 ºC is consistent with an analysis of plot data from Australian temperate forests by Bowman et al. (2014) who noted maximum growth occurring at a mean annual temperature of 11 °C and maximum temperature of the warmest month of 25–27 °C. They found that lower temperatures directly constrained growth whilst high temperatures primarily reduced growth by reducing water availability.

Radiation-use-efficiency (RUE) across Australasian ecoregions was tightly coupled with GPP and was similar (but perhaps higher) than the international relationship (Fig. 6d). There is a similarly large range in RUE across Australian ecoregions, from pasture (0.65 gC MJ PAR^{-1}), temperate and Mediterranean woodland (0.75 gC MJ PAR^{-1}), tropical savanna (1.0 gC MJ PAR^{-1}) and temperate and tropical forest (1.5 gC MJ PAR^{-1}). Global values across FluxNet showed RUE to be approximately 0.2 gC MJ PAR $^{-1}$ and 0.35 gC MJ PAR $^{-1}$ for grassland and savanna respectively (Reichstein et al., 2014). The correlation between RUE and GPP decreased when GPP was expressed per unit LAI (i.e. GPP / LAI – see Fig. 5) suggesting that all Australian ecosystems have similar efficiency per unit leaf and converge toward a similar biochemical efficiency.

The ecosystem water-use-efficiency (WUE*) of Australian systems was systematically lower than the global relationship (Fig. 6c) suggesting that these ecosystems have a low C gain per unit water loss. This surprising result is likely to reflect high soil evaporation ratios from open canopied woodlands and shrublands of the arid/semi-arid regions that dominate Australia. Haverd et al. (2013a) showed in BIOS2 modelling that over half (64%) of Australian ET is attributable to soil evaporation, which is much higher than the global fraction of 27%, that results in higher water loss per unit of C gained at the ecosystem scale. There are other important factors that could explain the smaller ecosystem WUE* of the non-arid Australian systems including: 1) it may reflect reduced leaf-scale instantaneous transpiration efficiency (ITE=A/E) (Barton et al., 2012); 2) the high degree of sclerophylly of Australian vegetation whereby C assimilation rates per unit leaf area will be low (compared to the USA or European flora) because of the large investment in thick cell walls and defensive compounds characteristic of long-lived sclerophyllous leaves (Eamus and Prichard, 1998); 3) leaf-level ITE of deciduous species is generally larger than that of evergreen species (Eamus and Prichard, 1998; Medina and Francisco, 1994) and the flora of US and European broadleaf forests are almost exclusively deciduous; 4) optimality theory of stomatal behaviour predicts that ITE is inversely proportional to VPD (Medlyn et al., 2011) and since mean VPD is generally larger in Australia than the US and Europe, a smaller ITE is expected for Australian sites compared to global analyses that omit Australian sites and 5) low soil nutrient availability of Australian soils (McKenzie et al., 2004) that limits photosynthetic capacity, reducing ITE (Schutz et al., 2009).

The WUE* and IWUE* of Australian sites ranged from 0.5 to 3.5 gC kgH_2O^{-1} and 5.6 to 29.8 gC hPa kgH_2O^{-1}, respectively (Table 3), which is lower than global estimates (Beer et al. (2009). A direct comparison with global results is difficult due to the dissimilar ecosystem types; however, Beer et al. (2009) obtained values of 3.1 gC kgH_2O^{-1} and 30.3 gC hPa kgH_2O^{-1} for WUE* and IWUE*, respectively, in the evergreen broadleaf biome type. Across similar C3 broadleaf systems in Australia, both WUE* and IWUE* were lower at 2.2 gC kgH_2O^{-1} and 16.7 gC hPa kgH_2O^{-1}. Previous research using Australian data have shown WUE* to be largest in evergreen broadleaf forest (EBF) sites (~3.0 gC kgH_2O^{-1}), followed by savanna sites (1.5 gC kgH_2O^{-1}) and grassland (~0.9 gC kgH_2O^{-1}) (Shi et al., 2014). They demonstrated the climate dependency of WUE* on VPD and soil water content, hence the preferred use of IWUE* here. Eamus et al. (2013b) examined WUE* and IWUE* for a tropical Mulga woodland and observed: 1) that daily WUE* declined with increasing soil moisture content in both wet and dry seasons and declined with increasing VPD only in the dry season, a result attributed to an interaction of soil moisture content with VPD in the wet; 2) IWUE* declined with increasing soil moisture content and increased with increasing VPD in both seasons.

5 Synergies with modelling and remote sensing

5.1 Synergies between remote sensing and the OzFlux network

Satellite derived meteorology and optical spectral vegetation indices (VIs) have been used extensively to scale flux tower datasets in space and time (Chen et al., 2007; Huete et al., 2008; Muraoka and Koizumi, 2008; Verma et al., 2014). Satellite- derived land cover data provide information on spatial variations in vegetation type and structure, which is then used to interpolate between flux tower sites. Moreover, intra-annual and long term remote sensing products can elucidate the timing of plant growth / seasonality (Ma et al., 2013) and extent of prior climate, fire, land use, and disturbances, thus helping better understand observed fluxes (Asner, 2013; Baumann et al., 2014; Wulder and Franklin, 2006). In some instances, satellite data have been used to gap fill meteorological data when required for the generation of model drivers and annual budgets (de Goncalves et al., 2009; Reichle et al., 2011; Restrepo-Coupe et al., 2013). Vegetation indices and other biophysical products (e.g. MODIS LAI and fPAR) constitute measures of ecosystem structure (e.g. quantity of leaves, (Sea et al., 2011) and function (e.g. quality of leaves) and represent the phenological drivers of productivity, transpiration and other key ecosystem fluxes (Restrepo-Coupe et al., 2015; Zhang et al., 2010). Therefore, quantification of surface characteristics via satellite products improves flux studies and provides a more robust analysis of carbon, energy and water cycles. The integration of eddy covariance and remote sensing datasets has driven recent efforts to measure optical properties at flux sites, closing the gap between sampling of temporal and spatial scales (Gamon et al., 2006, 2010).

Conversely, flux data and ancillary *in situ* measurements associated with eddy covariance systems have been extensively used for the validation of different satellite products (e.g. MODIS GPP and ET (Kanniah et al., 2009b; Restrepo-Coupe et al., 2015)) and to assist in the parameterisation of models that rely on remotely sensed data (e.g. GPP, ET, canopy conductance, and light use efficiency (LUE)) (Barraza et al., 2014, 2015; Glenn et al., 2011; Goerner et al., 2011). Given the challenge of managing water in the dry Australian continent, remote sensing of actual ET is a crucial task and Glenn et al. (2011) provide an overview of the Australian experience in this task. Similarly, *in situ* fluxes can provide the basic information required for the interpretation of satellite derived measures of greenness (Huete et al., 2006, 2008; Restrepo-Coupe et al., 2015). Recently, comparisons between flux data and satellite products have been proposed as a tool to evaluate sensor continuity, e.g. transition from MODIS derived VIs to the Visible - Infrared Imaging Radiometer Suite (VIIRS) instrument (Obata et al., 2013). Ground-based flux tower measures, however, offer much more than validation of remote sensing products and models. An understanding of why satellite – flux tower relationships hold or don’t hold can greatly advance and contribute to our understanding of mechanisms underpinning carbon and water cycles and scaling factors.

Finally, flux tower information for Australia has been used in empirical upscaling methods (such as machine learning) that use gridded satellite information and meteorology to produce global estimates of carbon and water budgets (Jung et al., 2009, 2011). These utilised some of the earlier data from Howard Springs, Tumbarumba and Wallaby Creek in the la Thuile fluxnet database that helped constrain the global uncertainties.

5.2 Synergies between terrestrial biosphere modelling and the OzFlux network

Development and validation of terrestrial biosphere models are reliant on observational data. Here we refer to examples of the utility of OzFlux data for advancing these models. OzFlux data were instrumental in constraining a continent-wide assessment of terrestrial carbon and water cycles (Haverd et al., 2013a). That paper explored the utility of multiple observation types (streamflow, measurements of evapotranspiration (ET) and net ecosystem production (NEP) from 12 eddy-flux sites, litterfall data and data on carbon pools) to constrain a terrestrial biosphere land surface model of Australian terrestrial carbon and water fluxes. They conclude that eddy flux measurements provide a significantly tighter constraint on continental net primary production (NPP) than all the other data types. Nonetheless, simultaneous constraint by multiple data types is important for mitigating bias from any single type. Four significant results emerged from the multiply constrained model of the 1990–2011 period: 1) on the Australian continent, a predominantly semi-arid region, over half the water loss through ET (0.64 ± 0.05) occurred through soil evaporation and bypassed plants entirely; 2) mean Australian NPP was quantified at 2.2 ± 0.4 PgC yr^{-1}, with a significant reduction in uncertainty compared with previous estimates; 3) annually cyclic ("grassy") vegetation and persistent ("woody") vegetation accounted for 0.67 ± 0.14 and 0.33 ± 0.14 PgC yr^{-1}, respectively, of NPP across Australia; 4) the average inter-annual variability of Australia's NEP (±0.18 PgC yr^{-1}) was larger than Australia's total anthropogenic greenhouse gas emissions in 2011 (0.149 PgC equivalent yr^{-1}) and was dominated by variability in semi-arid regions. Results from the above model-data synthesis were used to produce major flux components of the first ever full terrestrial carbon budget of Australia (Haverd et al., 2013b) as part of a larger international effort to reconcile bottom-up and top-down estimates of the global carbon budget. Further applications include an assessment of the climate sensitivity of Australian carbon and water cycles (Raupach et al., 2013) and an assessment of the magnitude of the Australian contribution to the record global sink anomaly of 2011, with counter-evidence to the assertion by Poulter et al. (2014) that Australian semi-arid ecosystems have entered a regime of increased sensitivity of NEP to precipitation (Haverd et al., 2015).

OzFlux data have also featured in the development of new models. For example, they have been used as constraints and validation for reductionist approaches to modelling evapotranspiration and canopy conductance at continental Australian (Guerschman et al., 2009) and global scales (Yebra et al., 2012). They have also been critical to the development of novel model parameterisations for heat storage in vegetation (Haverd et al., 2007), in-canopy turbulence (Haverd et al., 2009), stable-isotope transport in soil and vegetation (Haverd and Cuntz, 2010) and canopy radiative transfer (Haverd et al., 2012). More recently they have been employed as constraints in the development of a novel approach to modelling coupled carbon allocation and phenology in savanna ecosystems, leading to emergent predictions about the controls of tree cover in Australian savannas (Haverd et al., 2016). Alternate modelling strategies such as use of stomatal optimality theory has been developed and tested in Australian savannas using OzFlux data (Schymanski et al., 2008a, 2008b).

6 Future outlook

The OzFlux network has been highly successful in generating standardised measurements and protocols, as well as for providing advanced QA/QC data compatible with international databases (FLUXNET) (Papale et al., 2006) under an open access data policy. OzFlux has contributed to the FLUXNET community efforts to improve data processing algorithms to minimise potential errors associated with night-time bias, gap filling and lack of energy balance closure (Baldocchi, 2003; van Gorsel et al., 2009). This has enabled a significant uptake of the eddy covariance data for application to a range of research questions as exemplified above. OzFlux is also aligned with the long-term plan for Australian ecosystem science (Andersen et al., 2014).

Dynamic global models are based on the notion that the same environmental controls will produce the same vegetation structure irrespective of environmental and evolutionary history (Lehmann et al., 2014). The unique evolutionary history of the Australian continent, climate and vegetation underpins the importance of the OzFlux network as it provides Australian derived data for key ecosystem metrics such as NEP, GPP, RUE and IWUE* for use in continental and global vegetation models. Despite the dominance of the semi-arid/arid climate and the importance of semi-arid ecosystems in Australia and globally, there still remains a gap in our knowledge about the effect of soil water deficits, soil evaporation, extreme temperatures and vapour pressure deficits (Eamus et al., 2013b) both as ecosystem drivers and as extreme events that accompany drought. Currently, ecosystem response to drought is not well understood, particularly because low precipitation events themselves are unpredictable in timing, duration and severity. It is expected that the frequency and severity of drought will increase with climate change; therefore, our current understanding of responses to rainfall scarcity will aid in our understanding of ecological responses to future climate and the potential consequences and adaptation that may be required. A number of drought related questions can be addressed by OzFlux including: 1) how do droughts affect physiological processes such as photosynthesis at leaf to landscape scales; 2) what is the effect of seasonal droughts *versus* multi-year droughts; 3) are there critical thresholds or compensatory reductions in productivity due to drought; and 4) are there multi-year drought legacy or feedback effects?

We have demonstrated that OzFlux has already contributed to other areas of importance such as ecosystem responses to fire, pest outbreaks, cyclones, and the impact of land use and land cover change (including urban flux systems (Coutts et al., 2007, 2010)) (Baldocchi, 2014a). Future climate is likely to be more variable and extreme and the network is well placed to capture and understand these events (Frank et al., 2015).

While there is no significant influence of temperature on NEP or GPP across Australian biomes the strong dependence of these variables on MAP indicates that even in currently well-watered areas the combined effect of increased temperature and VPD, similar or reduced water availability will potentially place these systems under stress. OzFlux then is well positioned to provide continuous assessment of the long-term condition of these ecosystems and provide early warning across multiple ecosystems of changes in plant performance as the planet moves into the more forceful climate of the Anthropocene. It should be noted that the network is relatively young with only 3 sites with data over 10 years. As such the ability for OzFlux in conjunction with other TERN platforms to decipher long term trends is currently a limitation that can be improved only with time.

There are also opportunities for OzFlux to play a core role in investigating processes within the 'Critical Zone', defined as the Earth's outer layer from vegetation canopy and through the soil and groundwater that sustains human life (Lin, 2010). Critical zone science extends us from the thin surface layer to the larger critical zone domain that allows a comparison of the environmental effects across gradients of climate (Cernusak et al., 2011), time, lithology, human disturbance, biological activity and topography (Lin, 2010). This should also involve a focus on greenhouse gas exchanges (not just CO_2 but also N_2O and CH_4) from the soil and understanding the linkages with microbial and rhizosphere processes (Hinsinger et al., 2009; Livesley et al., 2011). Some of OzFlux contribution here can be to utilise overstorey and understorey flux measurements to understand the role of distinct understorey vegetation such as the grasses versus trees in savannas (Moore et al., 2015)

Baldocchi (2014b) reminds us that additional ecological and physiological measurements (function, structure, pools and turnover) add significant value to our flux data and are required for modelling carbon pools. OzFlux works closely with the SuperSite Facility (Karan et al., 2016) in TERN as each SuperSite is required to co-host an OzFlux tower. Over the last 4 years ecophysiological data have been collected across 7 sites and along with prior data from a number of OzFlux sites this has allowed an early assessment of plant performance to be made across many of the OzFlux sites. The SuperSites facility complements the OzFlux measurements by measuring the biotic community and biophysical environment. Co-location of activities for both facilities has been important as this has enabled both networks to share resources and survive through tough financial times. Like any long-term network in Australia this ability to survive is a hall-mark of success (Lindenmayer et al., 2012). Hence, it is imperative that going forward OzFlux enhances and utilises the synergies and research collaborations between OzFlux and other TERN platforms such as remote sensing (AusCover), modelling (eMAST) and plot networks such as transects, AusPlots and the long term ecological research network (LTERN). No single capability is able to address all of the spatial, ecological, human and cultural challenges required. Instead a synergistic approach (Peters and Loescher, 2014) that is policy relevant (with political commitment) is required to monitor and manage our planet.

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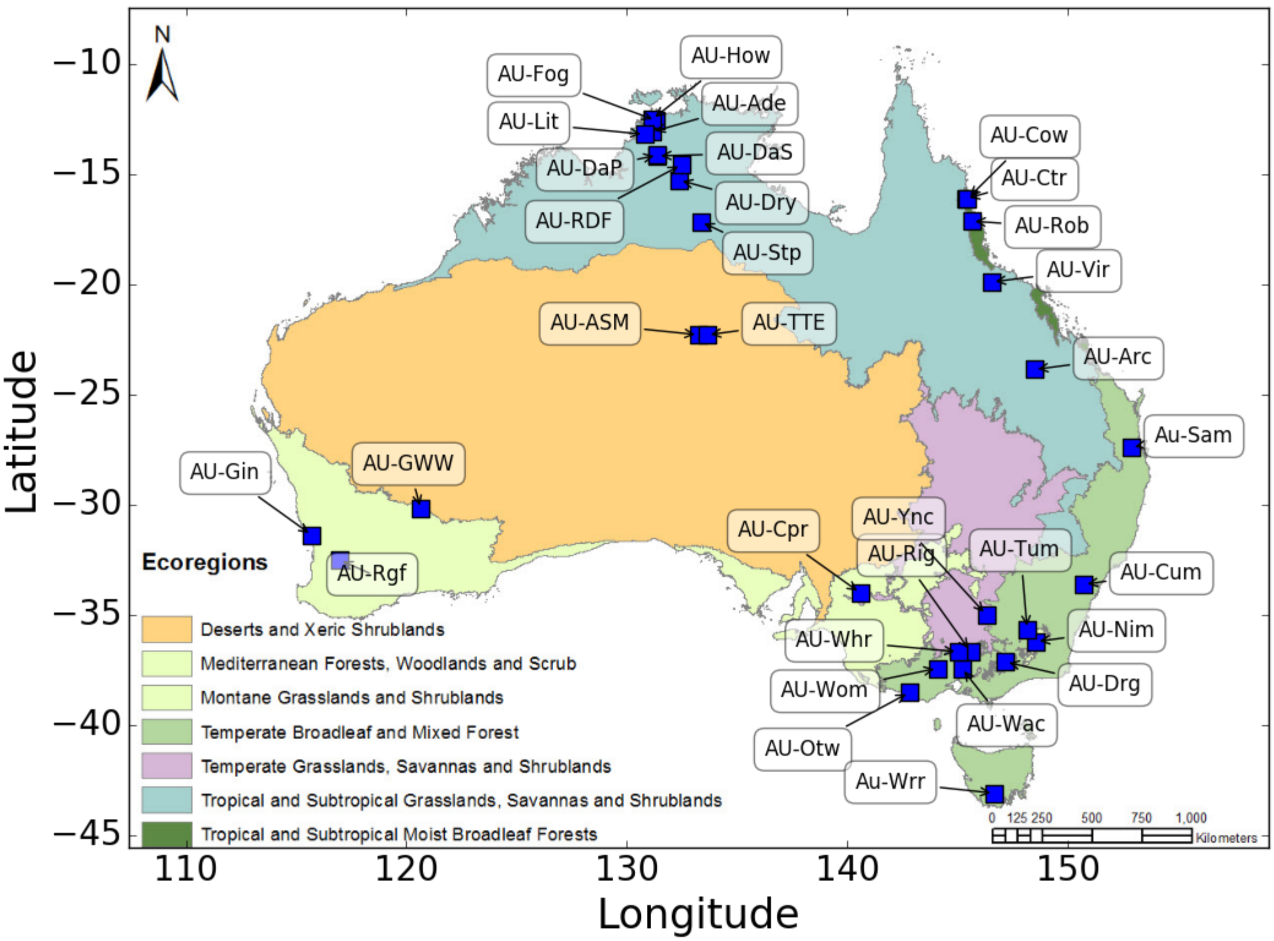

Figure 1: Major Australian biomes defined using the Interim Biogeographic Regionalisation for Australia v. 7 (IBRA) (Environment, 2012). Flux sites from Table 1 are shown illustrating the wide geographical and biome space but each biome is not equally represented. Only a small fraction of the OzFlux sites (8%) are located in the arid/semi-arid biomes that comprises 74% of the landscape.

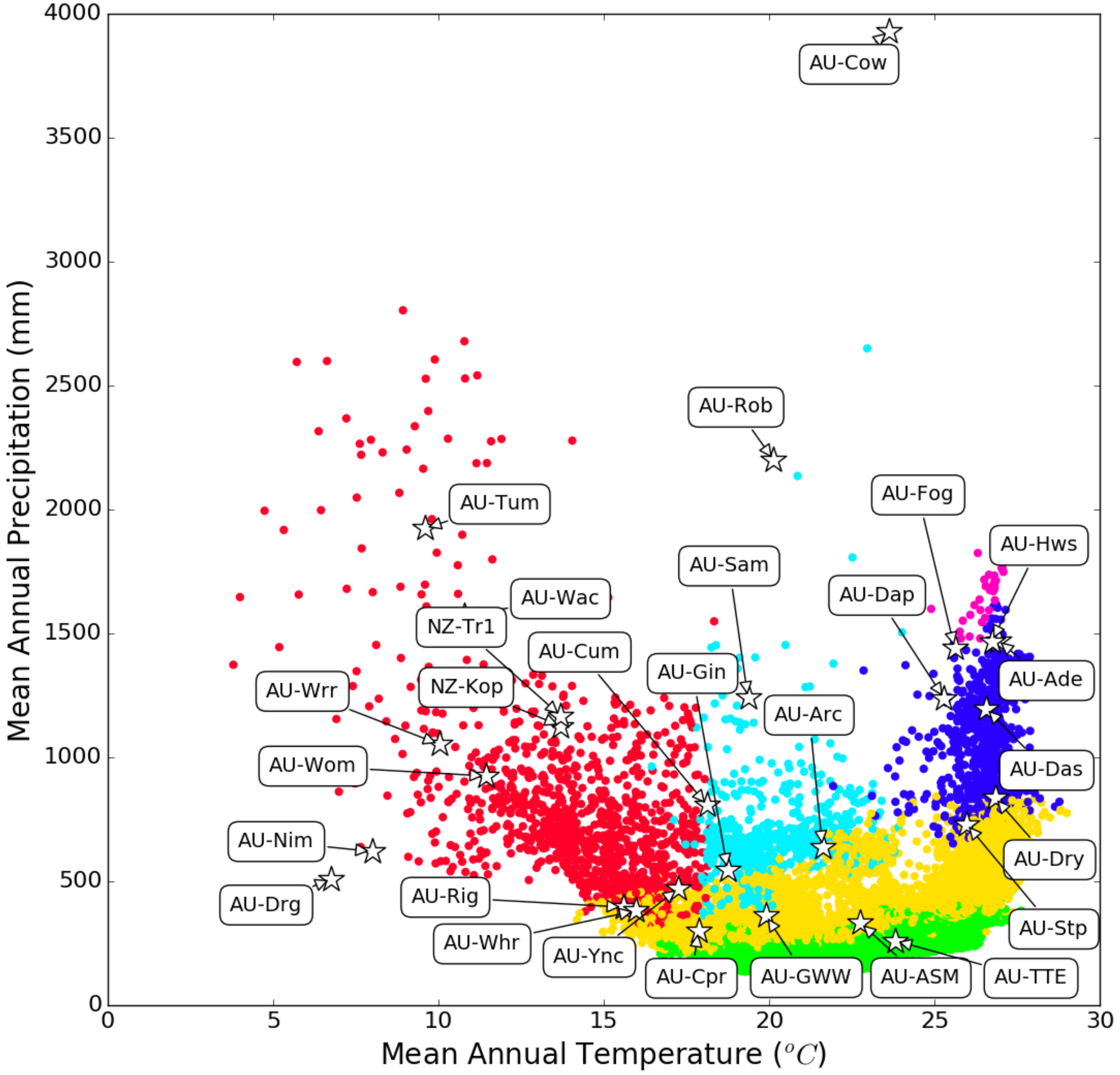

Figure 2: OzFlux sites (white stars) across bioclimatic space with Fluxnet codes (Table 1). Mean annual temperature and mean annual precipitation are shown as the climate space using mean annual (1961-1990) gridded data (0.1 degree resolution) *(Bureau-of-Meteorology, 2013)*. The colours represent the major modified Köppen climate classes (Stern and Dahni, 2013) as follows: 1) Equatorial (Pink), Tropical (Dark Blue), Sub-tropical (Light Blue), Desert (Green), Grassland (Yellow) and Temperate (Red).

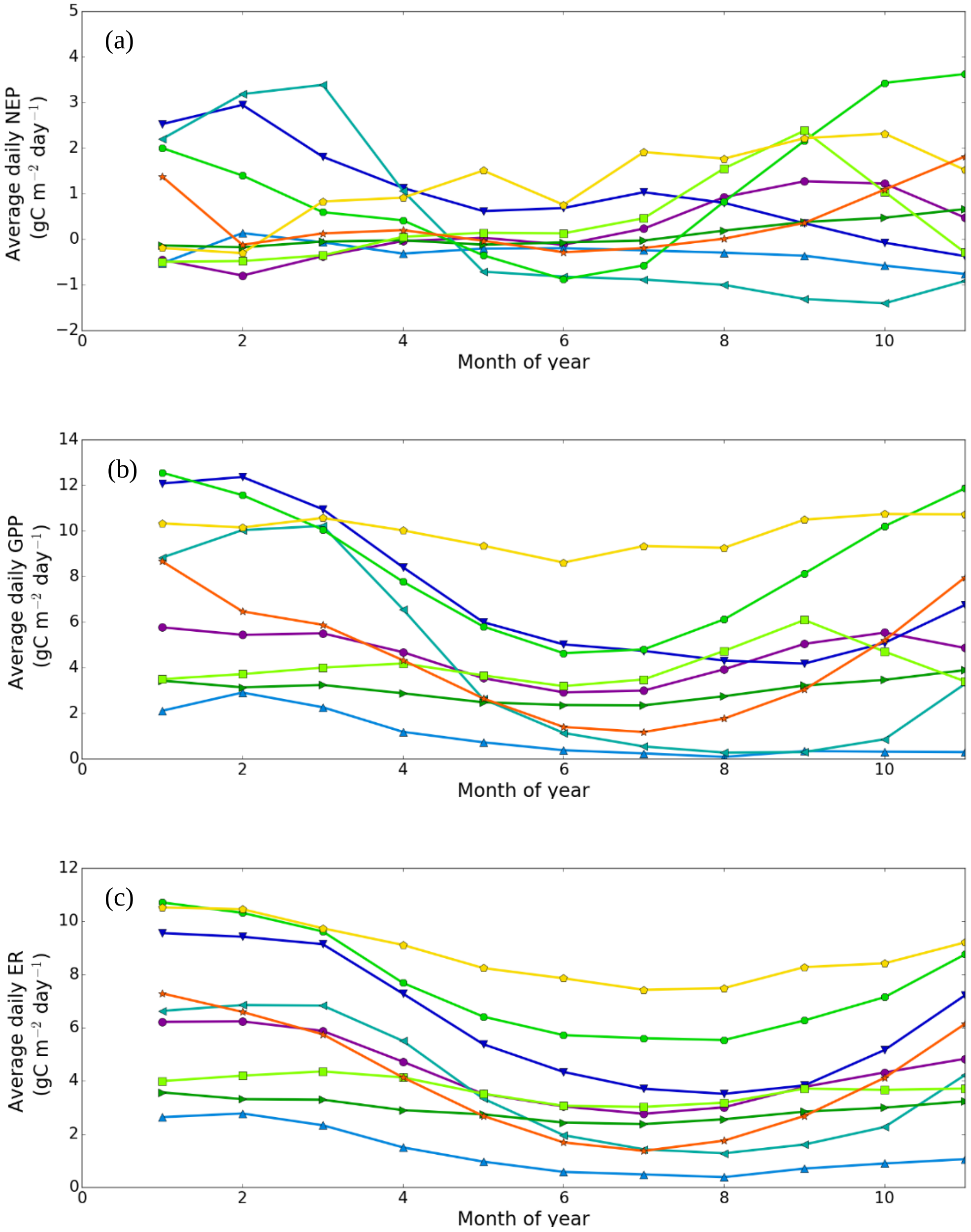

Figure 3: Weekly ensemble from the Australian OzFlux sites of the measured Net Ecosystem Productivity (NEP) (a) and component Gross Primary Production (GPP) (b) and Ecosystem Respiration (ER) (b) for all OzFlux tower sites in each biome as follows ●—● temperate woodlands, ▼—▼ tropical savannas, ▲—▲ desert shrublands, ◀—◀ tropical grasslands, ▶—▶ mediterranean woodands, ●—● temperate broadleaf forests, ■—■ pasture, ⬟—⬟ tropical moist broadleaf forests and ★—★ montane grasslands. The sites used in each biome are shown in Table 1. GPP generally scales with Leaf Area Index (LAI) and water availability. Most of the variability follows the respective rainfall patterns associated with the tropical, mediterranean, and temperate climates.

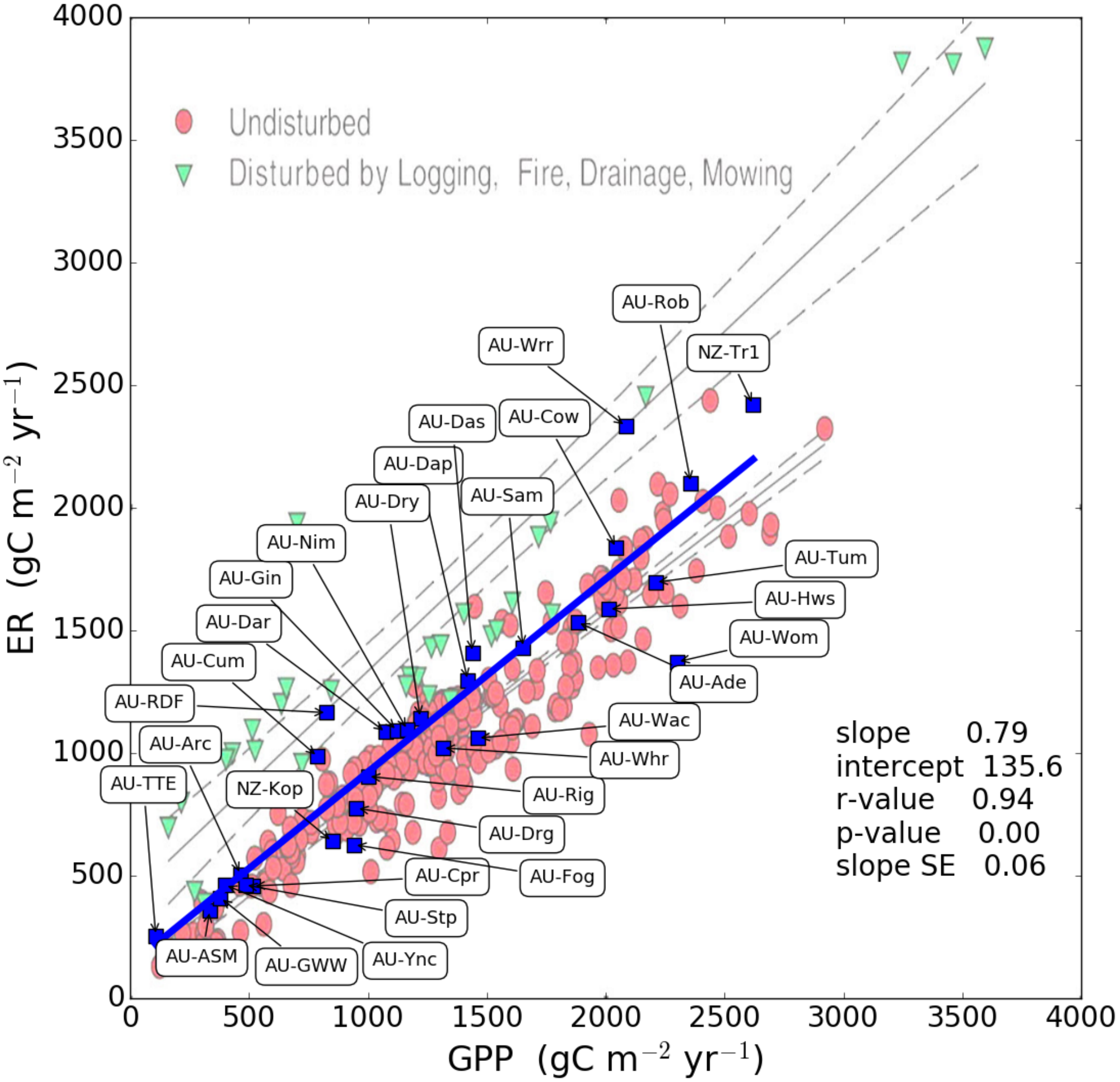

Figure 4: Relationship between site averaged Ecosystem Respiration (ER) and Gross Primary Production (GPP) for all OzFlux tower sites (blue squares) showing they are well correlated (r^2=0.93) with a slope of 0.76. This compares with slope of 0.77 in an international synthesis by Baldocchi (2008). The results from the international study (red and green symbols) are shown in the background and show a secondary line where disturbed sites (green triangles) had large positive values of Net Ecosystem Productivity (NEP) (carbon source). Few Australian sites reach that level of disturbance. Solid lines are regressions, dashed lines are 95 % confidence intervals.

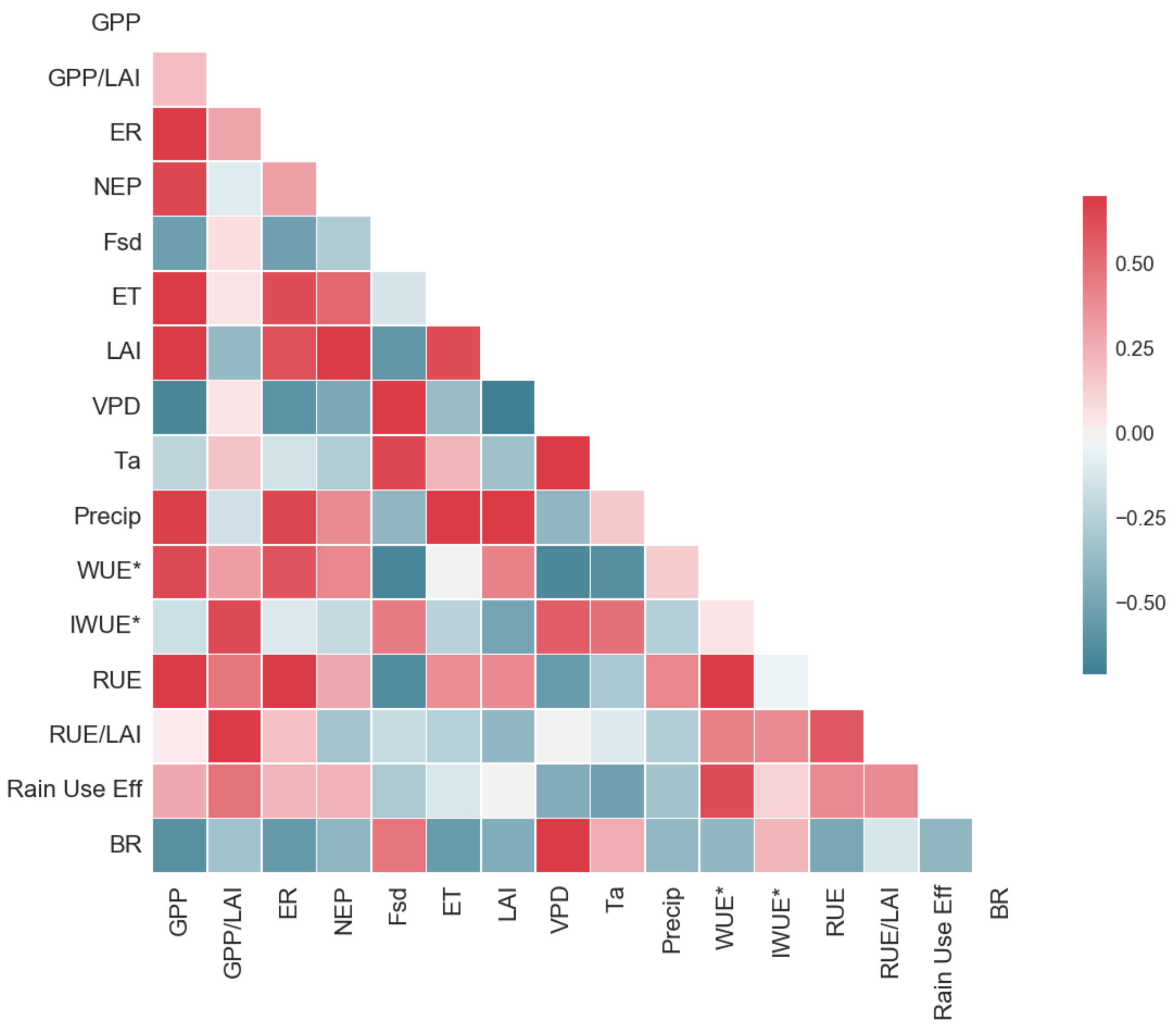

Figure 5: Simple heat map of Australian OzFlux tower measurements to identify the correlations between fluxes, driving variables and ecosystem indices using all site averaged data for available site years to represent spatial variability. Fluxes are gross primary productivity (GPP), ecosystem respiration (ER), net ecosystem production (NEP), evapotranspiration (ET). Drivers are leaf area index (LAI), precipitation (Precip), air temperature (T_a), incoming solar radiation (F_{sd}) and vapor pressure deficit (VPD). We used the following ecosystem indices: radiation use efficiency (RUE) following Garbulsky et al. (2010); ecosystem water-use-efficiency (WUE*) and inherent ecosystem WUE* (IWUE*) following Beer et al. (2009); Bowen ratio (BR) is defined as the ratio between sensible and latent heat fluxes (Bowen, 1926); Leaf area index (LAI) was obtained from the average of the MODIS MOD15 product for the site years available that has been de-spiked using the procedure described in Kanniah et al. (2009a); and rainfall use efficiency was defined following Huxman et al. (2004) as the ratio of GPP to precipitation. GPP and RUE are also normalized by LAI by dividing them by LAI to produce series such as GPP/LAI. Colour scale indicates the strength of Pearson correlation co-efficient (r).

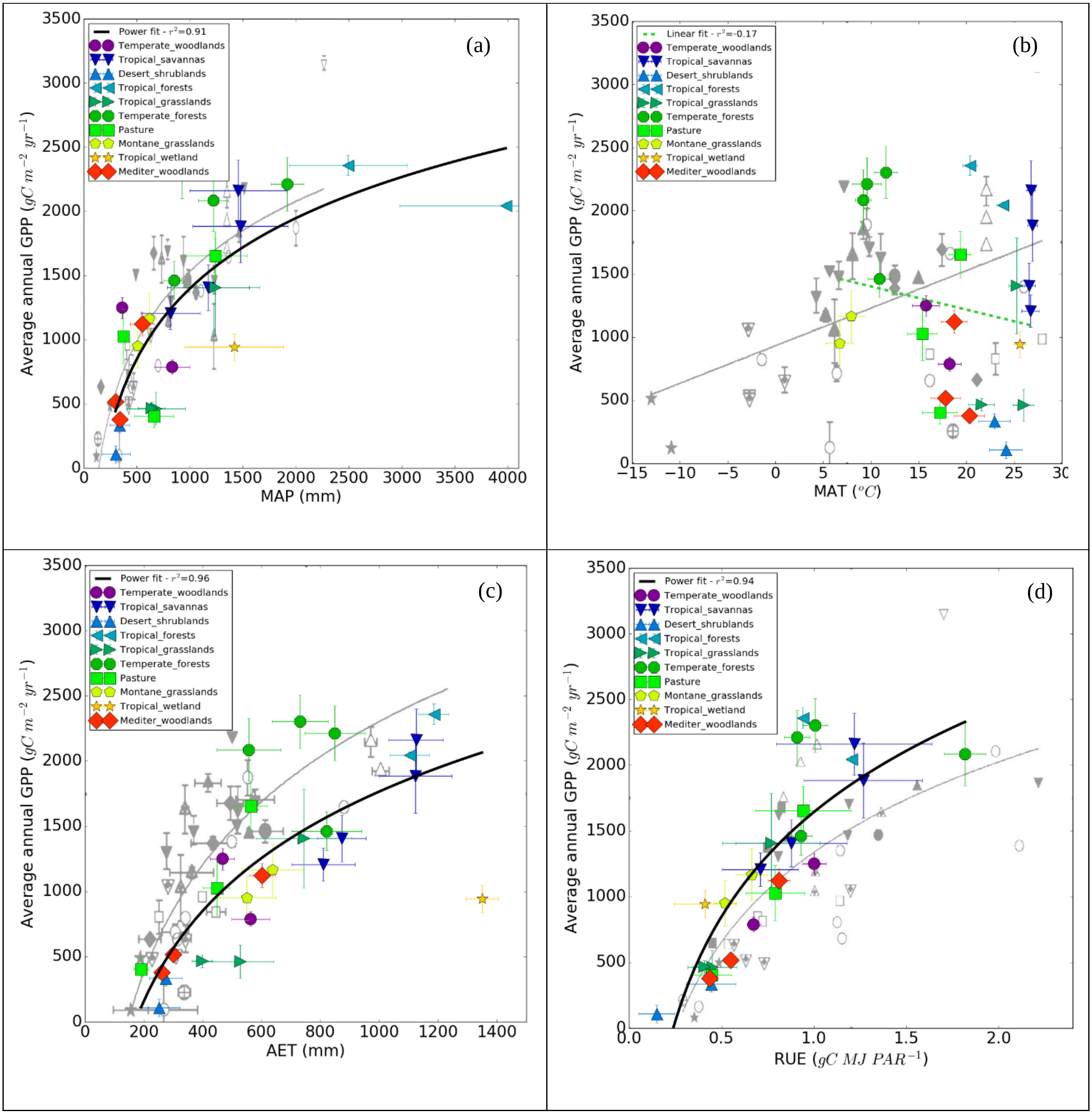

Figure 6: The relationships of Australian OzFlux tower data by ecoregion type (Table 1) between gross primary production (GPP) and the major climate drivers (a) mean annual precipitation (MAP) and (b) mean annual temperature (MAT). Also shown is the relationship between GPP and (c) actual evapotranspiration (AET) and (d) radiation use efficiency (RUE). The global relationships in Garbulsky et al. (2010) are shown in the background to aid comparison. Simple curve fits are shown to aid visualization.

Table 1: A summary of the OzFlux tower sites along with the available data range and site history. The associated IBRA vegetation class is given (IBRA) along with the broader world ecoregion classification, both from the Interim Biogeographic Regionalisation for Australia v. 7 (IBRA) (Environment, 2012).

Site name	FLUXNET ID	Date range	Latitude S	Longitude E	Elevation (m)	IBRA	World ecoregion
Adelaide River	AU-Ade	2007-2009	-13.0769	131.1178	100	PCK	Tropical savannas
Alice Springs	AU-ASM	2010-present	-22.2830	133.2490	606	BRT	Deserts and Xeric Shrublands
Arcturus	AU-Arc	2011-2013	-23.8587	148.4746	178	BBN	Tropical grassland
Calperum	AU-Cpr	2010-present	-34.0027	140.5877	53	MDD	Mediterranean woodands
Cape Tribulation	AU-Ctr	2001-present	-16.1056	145.3778	66	WET	Tropical and Sub-tropical moist broadleaf
Cow Bay	AU-Cow	2009-present	-16.1032	145.4469	86	WET	Tropical and Sub-tropical moist broadleaf forests
Cumberland Plains	AU-Cum	2012-present	-33.6153	150.7236	54	SYB	Temperate woodlands
Daly River Pasture	AU-DaP	2007-2013	-14.1331	131.3856	67	DAB	Tropical pasture
Daly River Savanna	AU-DaS	2007-present	-14.1592	131.3881	53	DAB	Tropical savannas
Dargo	AU-Drg	2007-present	-37.1334	147.1709	1648	AUA	Montane grasslands
Dry River	AU-Dry	2008-present	-15.2588	132.3706	180	STU	Tropical savannas
Fogg Dam	AU-Fog	2006-2008	-12.5452	131.3072	4	DAC	Tropical wetland
Gingin	AU-Gin	2011-present	-31.3764	115.7139	53	SWA	Mediterranean woodands
Great Western Woodland	AU-GWW	2013-present	-30.1913	120.6541	486	COO	Mediterranean woodands
Howard Springs	AU-How	2001-present	-12.4943	131.1523	41	DAC	Tropical savannas
Kopuatai	NZ-Kop	2012 - 2015	-37.3880	175.5540	5		Wetland
Litchfield	AU-Lit	2015-present	-13.1790	130.7945		DAC	Tropical savannas
Nimmo	AU-Nim	2007-present	-36.2159	148.5528	1337	AUA	Montane grasslands
Otway	AU-Otw		-38.5250	142.8100		SCP	Pasture
Red Dirt Melon Farm	AU-RDF	2011-2013	-14.5634	132.4775	171	DAB	Tropical savannas
Ridgefield	AU-Rgf	2015-present	-32.5061	116.9668		AVW	Pasture
Riggs Creek	AU-Rig	2010-present	-36.6499	145.5760	162	RIV	Pasture
Robson Creek	AU-Rob	2013-present	-17.1175	145.6301	710	WET	Tropical and Sub-tropical moist broadleaf forests
Samford	Au-Sam	2010-present	-27.3881	152.8778	87	SEQ	Pasture
Sturt Plains	AU-Stp	2008-present	-17.1507	133.3502	225	MGD	Tropical grasslands
Ti Tree East	AU-TTE	2012-present	-22.2870	133.6400	553	BRT	Deserts and Xeric Shrublands
Troughton Farm	NZ-Tr1	2012 - 2015	-37.7700	175.5000	54		Pasture
Tumbarumba	AU-Tum	2001-present	-35.6566	148.1517	1249	NSS	Temperate Broadleaf and mixed Forest
Virginia Park	AU-Vir		-19.8833	146.5539		EIU	Savanna

Wallaby Creek	AU-Wac	2005-2013	-37.4259	145.1878	738	SHE	Temperate Broadleaf and mixed Forest
Warra	Au-Wrr	2013-present	-43.0950	146.6545	121	TSR	Temperate Broadleaf and mixed Forest
Whroo	AU-Whr	2011-present	-36.6732	145.0294	143	VIM	Temperate woodlands
Wombat	AU-Wom	2010-present	-37.4222	144.0944	715	VIM	Temperate broadleaf forest
Yanco	AU-Ync	2012-present	-34.9893	146.2907	128	RIV	Temperate Grasslands

Table 2: Summary of the representation of Australian OzFlux tower sites within each ecoregion compared with the total percentage of the continent comprising this ecoregion (Environment, 2012). The mean carbon fluxes are given for each ecoregion type.

Ecoregion	Percentage of the continent comprising this ecoregion (%)	Percentage of flux towers in that ecoregion (%)	GPP (tC ha^{-1} yr^{-1})	NEP (tC ha^{-1} yr^{-1})	ER (tC ha^{-1} yr^{-1})
Tropical and subtropical moist broadleaf forests	<1	12	22.1	2.8	19.3
Temperate broadleaf and mixed forest	7	16	21.5	3.9	17.6
Tropical and subtropical grasslands, savannas and shrublands	30	28	14.1	1.7	12.4
Temperate grasslands, savannas and shrublands	3	16	14.5	3.4	11.1
Montane grasslands and shrublands	<1	8	10.6	1.2	9.4
Mediterranean forests, woodlands and scrub	11	12	6.7	0.2	6.5
Deserts and xeric shrublands	49	8	1.8	-1.1	2.8

Table 3: Site averaged data for all OzFlux towers for available data periods (Table 1) showing mean and standard deviation of the daily fluxes. Fluxes are gross primary productivity (GPP), ecosystem respiration (ER), net ecosystem production (NEP), evapotranspiration (ET). Drivers are leaf area index (LAI), precipitation (Precip), air temperature (Ta), incoming solar radiation (Fsd) and vapour pressure deficit (VPD). We used the following ecosystem indices: radiation use efficiency (RUE) following Garbulsky et al. (2010); ecosystem(*) water-use-efficiency (WUE*) and inherent ecosystem WUE* (IWUE*) following Beer et al. (2009); Bowen ratio (BR) is defined as the ratio between sensible and latent heat fluxes (Bowen, 1926); Leaf area index (LAI) was obtained from the average of the MODIS MOD15 product for the site years available that has been de-spiked using the procedure described in Kanniah et al. *(2009a)*; and rainfall use efficiency (Rain Use Eff) was defined following Huxman et al. (2004) as the ratio of GPP to precipitation. Some quantities are also normalized by LAI by dividing them by dividing by LAI to produce series such as GPP/LAI.

Site	Data years inclusive	GPP	GPP/LAI	ER	NEP	Fsd	Fn	LAI	VPD	Ta	Ah	Precip	WUE*	IWUE*	IWUE*_LAI	RUE	Rain Use Eff	BR	ET
		tC ha^{-1} yr^{-1}	tC ha^{-1} yr^{-1} m^2 m^{-2}	tC ha^{-1} yr^{-1}	tC ha^{-1} yr^{-1}	MJ m^{-2} d^{-1}	MJ m^{-2} d^{-1}	m^2 m^{-2}	kPa	ºC	g m^{-3}	mm yr^{-1}	gC kgH_2O	gC kgH_2O hPa	gC kgH_2O hPa m^2 m^{-2}	gC MJ PAR^{-1}	tC ha^{-1} yr^{-1} mm^{-1}		mm yr^{-1}
Adelaide River	2007-2009	18.8 ± 10.5	15.9 ± 5.2	15.3 ± 7.0	3.5 ± 5.0	20.5 ± 2.3	12.2 ± 2.5	1.1 ± 0.4	1.4 ± 0.5	26.9 ± 1.7	16.2 ± 4.7	1472.7 ± 1612.3	1.6 ± 0.4	21.1 ± 8.2	21.8 ± 12.9	1.2	12.8	0.7 ± 0.6	1120.8 ± 457.4
Alice Springs	2010-2014	3.2 ± 3.5	8.6 ± 5.9	3.5 ± 3.1	-0.3 ± 1.3	22.6 ± 3.7	11.2 ± 3.0	0.3 ± 0.1	2.1 ± 0.8	22.8 ± 5.7	6.9 ± 2.8	331.3 ± 451.3	1.9 ± 1.7	29.8 ± 18.9	108.8 ± 89.3	0.4	9.6	15.1 ± 21.4	263.9 ± 272.5
Arcturus	2011-2013	4.7 ± 3.1	6.6 ± 3.7	5.1 ± 1.3	-0.4 ± 2.7	19.6 ± 4.2	10.5 ± 3.2	0.7 ± 0.3	1.3 ± 0.5	21.6 ± 4.7	10.7 ± 2.8	638.8 ± 575.2	1.2 ± 0.6	13.8 ± 6.9	20.2 ± 8.3	0.4	7.3	2.1 ± 1.4	398.9 ± 165.7
Calperum	2010-2014	5.2 ± 2.3	10.5 ± 3.1	4.6 ± 1.5	0.6 ± 1.5	18.4 ± 6.9	8.7 ± 4.6	0.5 ± 0.1	1.3 ± 0.7	17.9 ± 5.3	7.5 ± 1.3	300.6 ± 312.8	1.7 ± 0.7	20.7 ± 10.9	44.2 ± 21.6	0.6	17.1	2.9 ± 2.0	300.4 ± 139.9
Cow Bay	2009-2014	20.5 ± 1.4	4.6 ± 1.1	18.1 ± 2.0	2.4 ± 2.3	12.1 ± 2.9	7.3 ± 2.2	4.7 ± 0.9	0.6 ± 0.1	23.6 ± 2.2	17.4 ± 2.5	3930.0 ± 4631.5	1.9 ± 0.4	11.0 ± 4.5	2.4 ± 1.1	1.3	5.2	0.1 ± 0.2	1087.1 ± 251.7
Cumberland	2013-2014	9.1 ± 3.1	7.4 ± 2.1	9.8 ± 3.5	-0.7 ± 3.0	12.6 ± 8.8	7.2 ± 5.3	1.3 ± 0.2	0.8 ± 0.3	18.1 ± 4.1	10.6 ± 2.8	806.3 ± 787.3	1.5 ± 0.7	11.7 ± 3.9	9.0 ± 3.5	0.4	9.7	0.7 ± 7.3	550.1 ± 273.1
Daly River Pasture	2007-2013	14.0 ± 13.5	6.9 ± 5.5	12.9 ± 8.1	1.1 ± 6.3	21.3 ± 2.1	10.9 ± 1.8	1.5 ± 0.8	1.4 ± 0.5	25.3 ± 2.9	14.6 ± 4.6	1237.8 ± 1701.0	1.5 ± 0.7	18.0 ± 6.6	13.7 ± 8.3	0.6	11.3	3.4 ± 4.0	740.7 ± 580.3

Daly River Uncleared	2007-2014	14.3 ± 6.7	11.6 ± 2.9	13.9 ± 5.7	0.5 ± 2.7	20.8 ± 2.3	11.8 ± 2.7	1.2 ± 0.3	1.6 ± 0.5	26.6 ± 2.5	14.5 ± 4.4	1197.5 ± 1550.0	1.6 ± 0.3	24.5 ± 8.4	22.2 ± 10.4	0.9	12	0.9 ± 0.5	869.6 ± 297.9
Dargo	2007-2014	9.5 ± 5.8	4.3 ± 1.5	7.8 ± 4.1	1.8 ± 2.0	16.6 ± 6.6	7.6 ± 5.5	2.1 ± 0.9	0.3 ± 0.2	6.8 ± 5.0	5.7 ± 1.3	509.2 ± 420.3	1.6 ± 0.4	5.6 ± 3.5	2.6 ± 1.1	0.5	18.7	0.3 ± 0.6	551.4 ± 331.8
Dry River	2008-2014	12.3 ± 4.9	10.3 ± 2.6	-11.4 ± 3.7	0.9 ± 2.4	22.0 ± 2.3	11.8 ± 2.5	1.2 ± 0.2	1.8 ± 0.6	26.8 ± 3.4	13.7 ± 4.6	836.4 ± 1093.2	1.6 ± 0.4	28.3 ± 13.2	26.7 ± 16.1	0.7	14.7	1.2 ± 1.1	805.4 ± 361.5
Fogg Dam	2006-2008	9.5 ± 3.8	4.2 ± 1.3	6.3 ± 0.8	3.2 ± 3.4	21.3 ± 2.4	13.4 ± 1.8	2.2 ± 0.3	1.0 ± 0.3	25.6 ± 2.4	17.1 ± 3.8	1440.2 ± 1650.0	0.7 ± 0.2	6.5 ± 1.2	3.0 ± 0.7	0.4	6.6	0.3 ± 0.3	1355.3 ± 260.6
Gingin	2011-2014	11.2 ± 3.2	12.8 ± 2.3	10.9 ± 1.5	0.3 ± 2.2	19.8 ± 7.0	11.0 ± 4.9	0.9 ± 0.2	1.0 ± 0.6	18.7 ± 4.9	10.2 ± 1.4	546.7 ± 479.5	1.9 ± 0.5	20.5 ± 14.5	22.0 ± 13.4	0.9	20.5	1.5 ± 1.3	601.1 ± 184.8
Great Western Woodland	2013-2014	3.9 ± 0.8	10.2 ± 1.7	4.1 ± 1.5	-0.2 ± 1.1	20.0 ± 6.3	11.4 ± 5.0	0.4 ± 0.1	1.5 ± 0.7	19.9 ± 5.2	7.8 ± 1.5	361.1 ± 430.1	1.6 ± 0.4	21.6 ± 9.1	55.7 ± 19.5	0.5	10.7	3.0 ± 1.3	261.7 ± 105.9
Howard Springs	2001-2014	20.5 ± 7.3	13.3 ± 2.7	16.3 ± 5.2	4.2 ± 3.3	20.2 ± 2.2	13.2 ± 2.4	1.5 ± 0.4	1.2 ± 0.4	26.7 ± 1.8	16.9 ± 3.8	1468.6 ± 1890.1	1.7 ± 0.3	21.3 ± 5.9	15.7 ± 8.0	1.1	14	0.6 ± 0.5	1135.1 ± 350.2
Kopuatai	2012 - 2015	8.5 ± 4.6	2.3 ± 5.7	6.4 ± 3.7	2.1 ± 5.6	14.9 ± 2.6	10.0 ± 2.1	3.7 ± 0.8	3.9 ± 1.8	13.7 ± 3.0	9.6 ± 1.4	1127 ± 400	1.43 ± 0.5	5.6 ± 2.8	1.5 ± 3.5	0.6	7.5	1.0 ± 0.7	592.9 ± 263.9
Nimmo	2007-2014	11.7 ± 7.3	6.6 ± 2.4	11.0 ± 5.9	0.7 ± 2.7	17.2 ± 6.9	9.0 ± 5.3	1.6 ± 0.5	0.4 ± 0.2	8.0 ± 4.9	6.1 ± 1.4	620.5 ± 443.2	1.8 ± 0.5	6.8 ± 3.9	3.9 ± 1.5	0.6	18.8	0.4 ± 0.3	637.0 ± 366.5
Riggs Creek	2010-2014	10.5 ± 8.0	8.1 ± 4.3	9.2 ± 3.0	1.3 ± 5.6	17.5 ± 7.5	8.2 ± 4.4	1.3 ± 0.9	0.9 ± 0.6	15.6 ± 5.4	8.1 ± 1.3	395.8 ± 397.6	2.2 ± 1.5	12.5 ± 9.8	17.5 ± 35.1	0.7	26.6	1.3 ± 1.7	462.7 ± 228.9
Robson Creek	2013-2015	23.7 ± 3.2	5.8 ± 1.3	20.6 ± 3.8	3.2 ± 2.3	18.2 ± 4.8	12.7 ± 3.3	4.3 ± 1.1	0.4 ± 0.1	20.1 ± 2.8	14.7 ± 2.4	2199.4 ± 2420.8	2.0 ± 0.4	8.7 ± 4.1	2.0 ± 0.7	1	10.8	0.4 ± 0.3	1185.8 ± 223.6
Samford	2010-2014	16.6 ± 7.2	9.3 ± 3.3	14.3 ± 5.1	2.2 ± 3.3	17.0 ± 4.2	9.9 ± 3.3	1.7 ± 0.3	0.9 ± 0.3	19.4 ± 3.9	11.3 ± 4.0	1240.6 ± 1430.2	2.8 ± 0.5	24.1 ± 10.0	14.3 ± 6.9	0.9	13.3	0.9 ± 0.5	564.2 ± 215.7
Sturt Plains	2008-2014	4.8 ± 5.0	7.5 ± 7.4	4.6 ± 2.5	0.2 ± 2.9	22.7 ± 2.4	9.9 ± 2.4	0.5 ± 0.2	2.0 ± 0.7	26.0 ± 3.9	11.1 ± 4.6	730.5 ± 1172.5	0.8 ± 0.5	13.1 ± 7.5	26.5 ± 15.9	0.4	6.5	3.8 ± 4.4	549.6 ± 427.4

Ti Tree East	2012-2014	0.4 ± 2.7	0.4 ± 5.9	2.2 ± 2.2	-1.8 ± 1.2	22.5 ± 3.9	9.6 ± 2.7	0.3 ± 0.1	2.4 ± 0.9	23.8 ± 6.0	6.1 ± 2.5	259.9 ± 468.2	0.5 ± 0.3	11.7 ± 8.1	30.3 ± 10.6	0	1.4	19.2 ± 23.0	214.0 ± 275.4
Troughton Farm	2012 - 2015	26.7 ± 8.2	7.9 ± .3.1	24.2 ± 7.7	2.0 ± 10.3	15.3 ± 3.1	7.89 ± 3.5	3.3 ± 1.1	4.0 ± 5.0	13.7 ± 5.4	9.6 ± 1.4	1167 ± 1317	3.4 ± 0.5	13.4 ± 18.9	4.1 ± 1.7	1.0	22.6	0.3 ± 0.5	726.4 ± 143.195
Tumbarumba	2001-2014	22.1 ± 7.7	5.3 ± 1.7	17.0 ± 6.5	5.1 ± 3.7	16.6 ± 7.0	8.7 ± 5.3	4.1 ± 0.6	0.5 ± 0.3	9.6 ± 5.3	6.4 ± 1.4	1924.2 ± 1400.4	2.6 ± 0.5	11.7 ± 7.6	2.8 ± 1.7	1	11.5	0.6 ± 0.3	850.7 ± 361.7
Wallaby Creek	2005-2013	19.8 ± 5.4	5.2 ± 1.2	10.4 ± 5.9	9.3 ± 6.7	12.1 ± 5.3	7.5 ± 5.3	3.9 ± 0.8	0.4 ± 0.3	10.8 ± 4.0	7.2 ± 1.3	1571.2 ± 1098.1	2.4 ± 0.9	9.9 ± 5.9	2.5 ± 1.4	1.3	12.6	0.3 ± 0.4	911.3 ± 472.2
Warra	2013-2014	22.1 ± 8.8	13.8 ± 2.0	23.8 ± 2.5	-1.7 ± 6.8	10.4 ± 6.1	2.5 ± 12.2	1.6 ± 0.7	0.4 ± 0.2	10.0 ± 2.7	7.1 ± 0.6	1053.0 ± 459.8	3.5 ± 0.7	11.9 ± 4.9	7.4 ± 1.3	2.8	21	-0.1 ± 0.6	643.2 ± 325.5
Whroo	2011-2014	13.0 ± 3.0	14.1 ± 2.8	10.0 ± 2.0	3.0 ± 2.2	17.7 ± 7.9	9.7 ± 5.8	0.9 ± 0.1	0.9 ± 0.5	16.0 ± 4.9	8.1 ± 1.2	381.3 ± 329.5	2.6 ± 0.5	23.2 ± 14.6	25.0 ± 15.2	1.1	34.2	1.4 ± 0.9	494.9 ± 157.7
Wombat	2010-2014	22.5 ± 7.3	5.5 ± 1.4	13.5 ± 4.6	9.1 ± 3.9	15.4 ± 7.3	10.4 ± 5.8	4.1 ± 0.7	0.4 ± 0.3	11.4 ± 4.1	8.0 ± 1.3	924.9 ± 567.4	3.2 ± 0.6	12.1 ± 8.5	3.0 ± 2.2	1.1	24.3	0.3 ± 0.5	724.2 ± 331.9
Yanco_JAXA	2012-2014	4.8 ± 3.6	8.0 ± 4.0	4.7 ± 1.7	0.1 ± 2.2	19.0 ± 7.7	9.5 ± 4.8	0.5 ± 0.3	1.3 ± 0.8	17.3 ± 6.2	7.1 ± 1.0	472.1 ± 374.6	1.9 ± 1.2	16.2 ± 9.1	37.9 ± 37.2	0.5	10.1	4.0 ± 4.5	266.5 ± 135.3